

Submicron Diffractive Gratings for Thin Film Solar Cell Applications

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Abstract

Surface texturing with submicron diffractive gratings in Si is employed to enhance solar spectrum absorption. Extensive modeling with rigorous coupled wave analysis codes confirms experimental measurements of reflected light as a function of wavelength. Subsequently, these codes are used to predict optimal diffractive grating configurations for thin Si cells that will simultaneously reduce reflection at the air/Si interface, efficiently couple light into diffracted orders that remain near the interface, and reduce the propagating light that is not diffracted but is transmitted straight through the Si.

Introduction

Diffractive gratings can be utilized to great advantage in solar cell applications. They can reduce light lost to reflection at the air/Si interface. This can be accomplished by reducing the number of reflected orders to just the zero reflected order with a grating whose pitch is less than the incident wavelength of light. In this case, the layer can be considered as a homogeneous layer of artificial index. Thus, with the proper choice of grating duty cycle and grating depth, the bulk Si will be index-matched to air and little or no light is lost in reflection. Moreover, this type of anti-reflection treatment is very broadband, compared to a thin film coating, and is therefore well-suited to the broad solar spectrum.

Decreasing the Si thickness is economically advantageous, attractive for low-weight applications, and desirable from a loss mechanism viewpoint where the optimum thickness should be a fraction of the minority carrier diffusion length [1]. However, the required absorption length is a function of the wavelength of light, increasing with increasing wavelength. One way to accommodate this effect in a thin Si solar cell is to redirect the light propagating within the Si along a path that is nearly parallel to the Si interface. At the same time, the efficiency of the light that propagates straight through the Si solar cell should be reduced for long wavelengths.

The above requirements can be accomplished simultaneously with a single frequency diffractive grating. The grating notation used in this discussion is shown in Figure 1, where Λ is the grating pitch, m_R are the reflected grating orders, Θ_R are the associated reflected angles, m_T are the transmitted grating orders, Θ_T are the associated transmitted angles, and λ_0 is the wavelength of light in a vacuum. The grating equation that relates the diffracted angle to the incident angle, wavelength of light, and material parameters is also given in Figure 1.

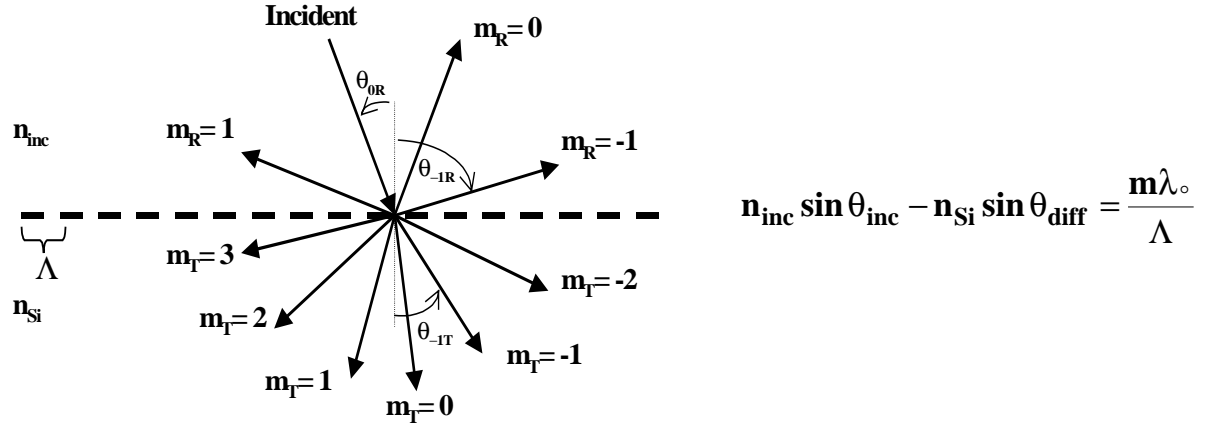


Figure 1. The grating equation and corresponding grating notation.

In this discussion we use a normal incidence configuration so that $\Theta_{inc} = 0$ degrees. Figure 2 shows the diffracted angle of the transmitted light within the Si substrate as a function of wavelength. Also shown are curves of the minimum diffraction angle required for a specific substrate thickness. These curves follow from the absorption coefficient of Si [2].

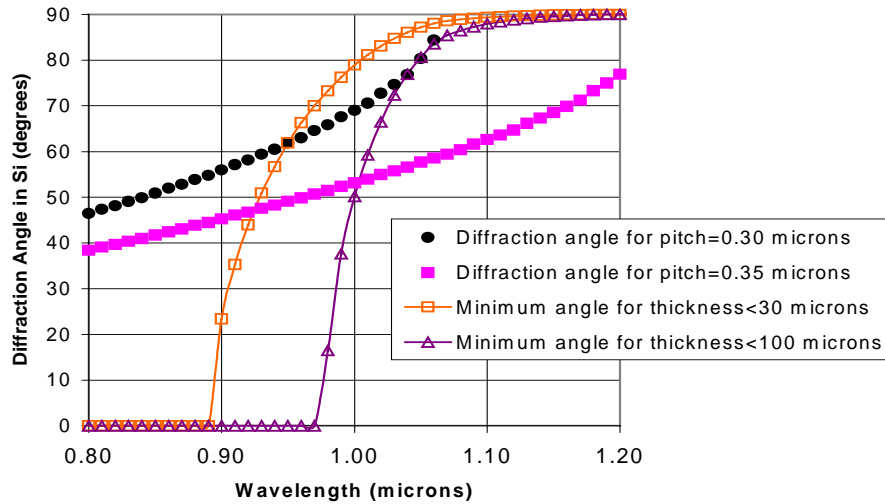
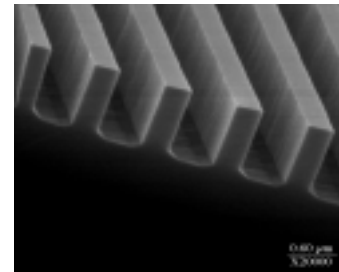
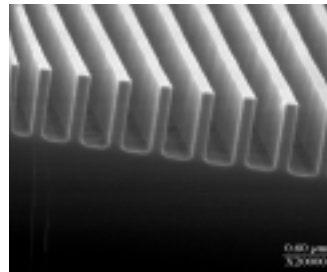
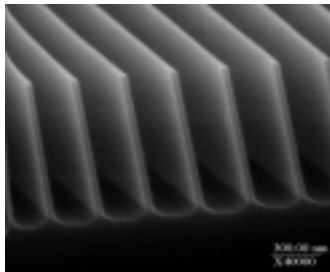


Figure 2. Diffraction angle as a function of wavelength for normal incidence.

Measurements and Predictions

A rigorous coupled wave analysis code [3] was used to predict the reflected efficiencies and confirm the experimental results shown in Figure 3 for the gratings below. Here, hemispherical reflectance refers to the sum of the efficiencies for all of the reflected orders.



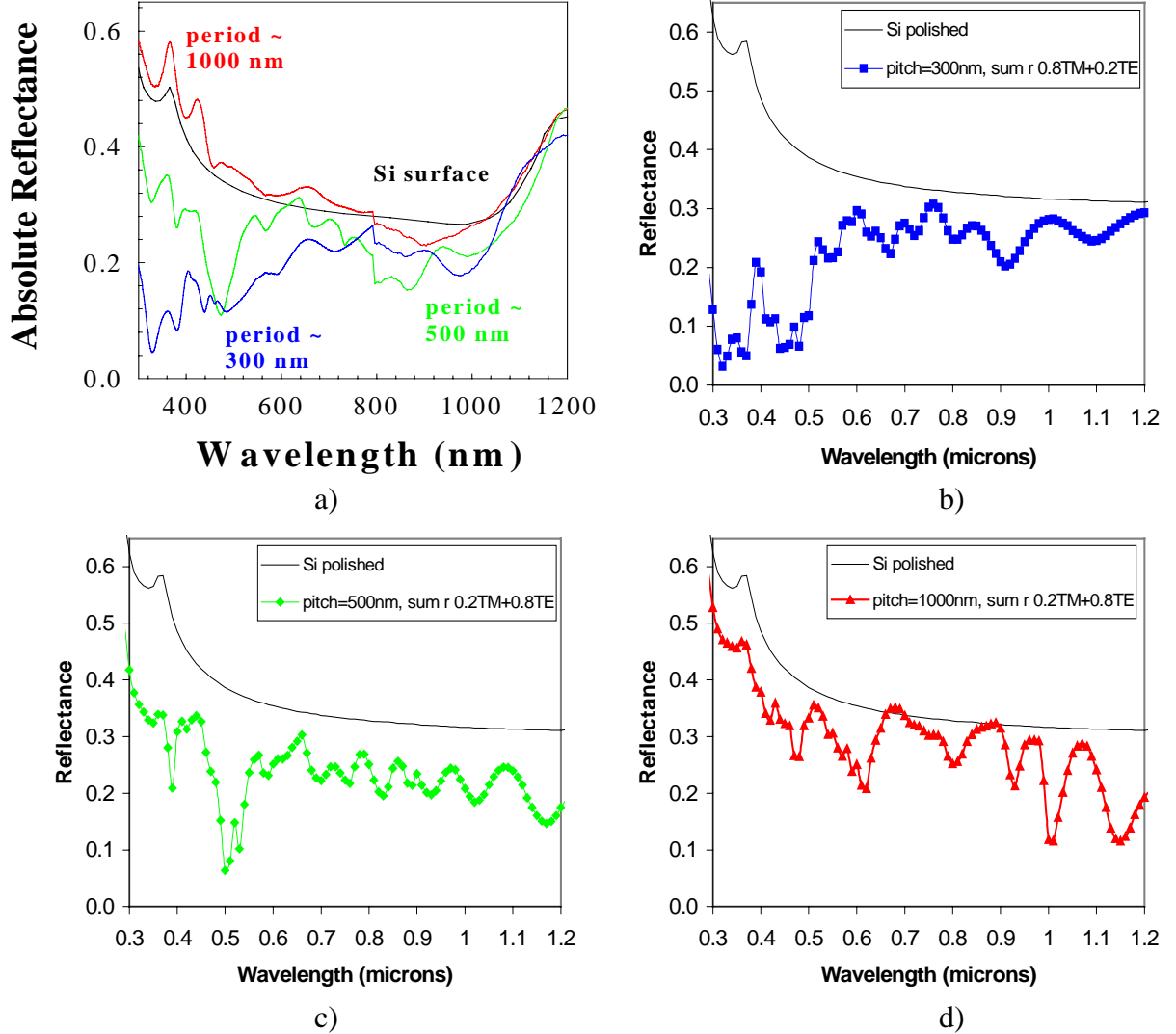


Figure 3. a) Measured hemispherical reflectance for the three gratings shown and a polished Si surface for reference. b)-d) Predicted hemispherical reflectance for the illustrated gratings above. The incident light is mostly linearly polarized and is designated TE if the E-field of the incident beam is parallel to the grating grooves.

In general, the model efforts agree with the above experimental results. One notable exception is the anomalous increase in reflectance present in all experimental configurations, including the polished Si surface. Theoretical modeling indicates that this increase in reflectance is actually light transmitted through the Si substrate, reflected at the back surface and retransmitted through the substrate. The advantage of modeling is that we can not only predict how much light is reflected, but also if light is efficiently coupled to the desired transmitting order. The above configurations are not optimal for this task.

Optimal Grating Designs

Next, we present two designs that approach our goals of minimum reflectance and maximum coupling of light into higher transmitted orders, especially for long wavelength light. Both designs have a pitch of $0.35\ \mu\text{m}$ so that the $\pm 1^{\text{st}}$ transmitted orders within the Si are diffracted at angles of approximately 60 degrees, for wavelengths above $1\ \mu\text{m}$. With this

constraint, the grating depth and duty cycle (linewidth divided by pitch) are adjusted to maximize coupling into the higher transmitted orders and to minimize coupling into the reflected and transmitted zero orders. Figure 4 illustrates the results of an optimal rectangular profile grating and an optimal triangular profile.

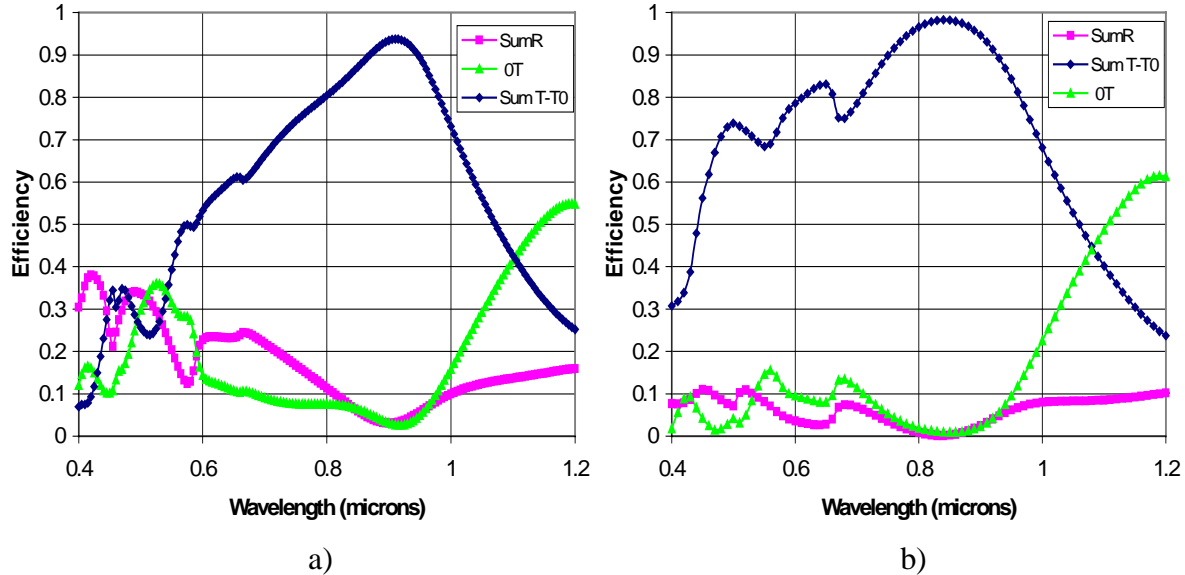


Figure 4. Coupling efficiencies for a) an optimal rectangular profile grating with depth=0.2μm and duty cycle=0.75 and b) an optimal triangular profile with depth=0.24μm and duty cycle=0.50.

The grating solution shown in Figure 4b) illustrates the excellent broadband antireflection response common to triangular profiles. Note that the exchange of energy between the higher order transmitted light and the zero order transmitted light is a function of the grating period. This crossover will move to the red end of the spectrum with increasing pitch, but with an accompanying smaller diffraction angle in the higher orders.

Conclusions

Theoretical modeling for grating design in solar cell applications saves fabrication time and effort when searching the large parameter space spanned by grating pitch, profile, depth, and duty cycle. Moreover, modeling allows us to direct light energy to specific orders within the substrate, a task that is difficult to characterize experimentally. In this project, we have identified two grating configurations that will each enhance solar cell absorption across the solar spectrum, particularly near the band-edge, by simultaneously directing the transmitted light to the appropriate orders while minimizing the light lost to reflection. Both grating profiles are simple solutions and can be fabricated with current technologies.

References

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